UCRL-TR-205723

Preliminary Report on Coining of Targets

P.J. Davis, M.A. Wall, N.E. Hodge, and A.J. Schwartz

August 4, 2004

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Auspices Statement

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Manufacturing Ultra-Precision Meso-Scale Targets by Coining
Preliminary Report

Pete J. Davis, Mark A. Wall, Neil E. Hodge, and Adam J. Schwartz

ABSTRACT

We were tasked with developing a coining technique that would evaluate the feasibility of using a pressing, or coining process to imprint a one-dimensional sinusoidal pattern onto a thin disk specimen. We performed finite element method simulations of the coining process, designed, built, and tested a coining apparatus and tested surrogate materials, and coined a sample of special nuclear material. The preliminary results were encouraging. The pressing of a 3-mm diameter by ~100 μm thick disc to 500 pounds of pressure produced a flat part with a 1-μm deep by 50-μm period sine wave pattern covering all of the surface and thus demonstrated the method for replicating ultra-precision, mesoscale features onto a near-net-shape metallic blank. This coining technique is being developed to provide specialty processing for the manufacturing of difficult to machine, millimeter-size components made from materials that present hazardous conditions. The technology is versatile and can be used to imprint a wide range of features, or profiles into two opposing surfaces. The coining process requires a simple, conceivably hand held tool, which efficiently produces ultra-precision work pieces without the production of byproducts such as machining chips, or grinding swarf. It shows promise for use on ductile materials that cannot be precision machined with conventional single crystal diamond tooling. As a production process, it can be used to reduce manufacturing costs where large numbers of ultra-precision, repetitive designs are required.

INTRODUCTION

There exists a certain type of experiment that requires a very precise, one or two-dimensional sinusoidal pattern to be imprinted on the surface of a thin disc-shaped specimen. Early discussions of potential fabrication processes included precision lapping using a substrate with the sinusoidal patterns, diamond turning, and various vapor deposition techniques. The process of coining, in which the sinusoidal pattern is pressed into the surface of a flat disc, was also proposed. Extensive discussions indicated that the low cost of coining and likelihood of success warranted this proof-of-principal investigation.

Lawrence Livermore National Laboratory is continually developing technology for manufacturing ultra-precision targets and target components for high energy density physics experiments. The products (an example is shown in Figure 1) are typically difficult to directly machine and often require complex machining set-ups and careful manipulation (handling). Samples made from radioactive or toxic materials, or materials that readily oxidize or hydride, present an exceptional challenge because they cannot be manufactured in a traditional open-air machining environment. Studies have shown that building or procuring fabrication, inspection, and assembly equipment for special facilities is costly. The economy of these methods is further compromised when maintenance and schedules are considered. The coining approach developed here takes advantage of the ductile nature (low yield strength and high elongation to failure) of the more problematic materials (i.e., radioactive and toxic). The modular system allows us to develop and qualify procedures using surrogate materials in a traditional environment, then transfer the work into a controlled workspace, such as a glove box.

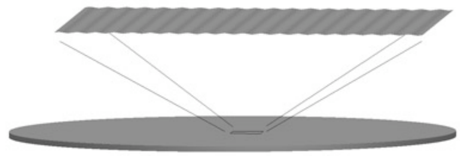

Figure 1. Schematic representation of a sinusoidal pattern fabricated onto a thin specimen.

For this development effort, we chose a 3-mm diameter by ~100-μm thick disc to be imprinted with a 1-μm deep by 50-μm period sine wave pattern covering the entire surface. Finite element analysis was performed to aid in the design of the coining press dies, a coining press was designed and fabricated, and surrogate and special nuclear material samples were coined and characterized. This document will describe the specimen requirements, modeling efforts, design and fabrication of the coining apparatus, the results of the coining on surrogate and special nuclear materials, and recommendations for future work.

Desired Sample Specifications

The initial design specifications are given below.

1) Target diameter and sweet spot = 4 mm
2) Thickness = 20 microns with flat and parallel faces to within ~2% of the thickness
3) Wavelength = 20 microns transitioning smoothly to 100 micron at the centerline of the target
4) Amplitude = +/- 0.5 micron (1 micron measured peak to valley)
5) Surface roughness, average (of the sinusoid) = one-tenth of the amplitude or 0.05 micron.

The Coining Apparatus

The coining apparatus is one element in the work piece forming system. The working elements include instruments to measure both displacement and force (pressure). The instrumented system shown in Figure 2 provides the ability to measure and control the total thickness variation of the sample. The system is designed to be implemented in two modes. During the development phase, the system has provisions for process feedback.

Parameters for given materials and shapes can be investigated with the aid of pressure and displacement gauging instruments. Once established, these parameters can be implemented without the aid of some, or all of the electronic instrumentation. This allows the self-contained unit to function in a range of environments. Such a requirement may occur for example, should in-situ annealing be specified. The hardware was designed and built to quickly assess the coining system's effectiveness on a specific class of materials.

Figure 2. Coining system: capacitance gage amplifier, coining press, and force meter (left to right).

Coining system hardware

To minimize the cost and complexity during this proof of principle investigation, the system was engineered to constrain all degrees of freedom except rotation and displacement. Tight control of parallelism and angular motion between the coining die surfaces reduces the requirements for precise near-net-shape target blanks. The mechanical design provides high angular stiffness thus reducing the chance of reproducing non-parallelism into the final product. The body, or cylindrical housing (Figure 3) of the unit is stiff and compact to mitigate the effects of temperature and compliance. Constructed from aluminum, it acts as a guide for the die plunger. To provide a smooth surface and clearance (2.5um) for contaminants, the bore is machined on a diamond turning lathe using a single point diamond (SPD) tool. After boring, and without disturbing the machining set-up, the body's critical face is surfaced. This provides less than 7 sec. arc. angular misalignment between the die and the guide bore that constrains the die plunger.

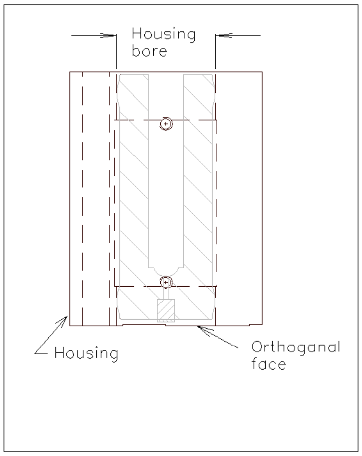

Figure 3. Cylindrical housing constructed from aluminum.

The die plunger contains two ultra-precision, diamond turned torroidal guide bearing surfaces. Torroidal surfaces are prescribed when there is a potential for cocking or binding to occur during the assembly of close fitting, precision surfaces. The plunger is designed to transmit load, guide the die, and act as a reference surface for measuring displacement (see Figure 4). The bearing surfaces and die face are SPDT on-axis in the same machining set-up. This turning and facing-to-center routine is preferable when producing products requiring one planar surface. Efficiency aside, the compact punch plate assembly is easier to support and fixture during complex machining and metrology set-ups.

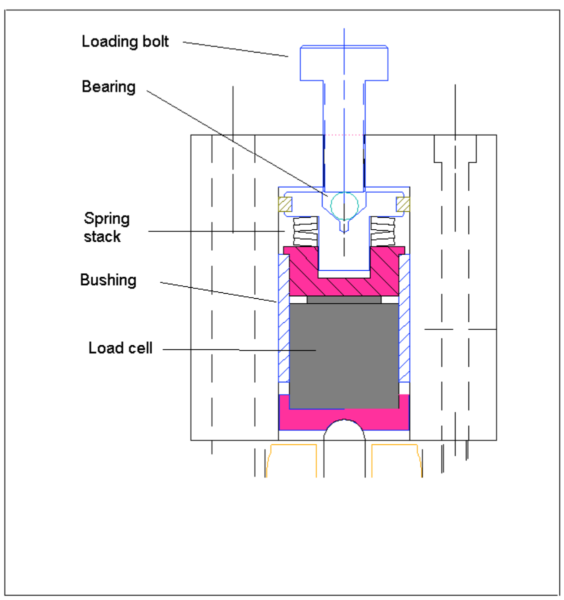

Figure 4. Cap assembly.

The punch plate supports and orients the aluminum housing and is fitted with the ultra-precision punch blank. For coined products requiring planar or 1D features, the profiled punch can be machined (diamond turned) off-axis in a lathing operation. Figure 5 shows a elevation view of the machining set-up. The punch plate is bolted to the machine's face-plate. Two assemblies are required, so for balancing purposes, they are located on opposite sides of the face-plate. Clocking each punch plate allows the housing support pads to be faced with a program that misses the protruding punch and only surfaces the pads. Programming a second operation provides the contouring tool path for surfacing contoured punch face. The housing support surfaces (pads) and the punch surface are machined in the same off-axis set-up to eliminate angular misalignment of the plunger housing. The total error sources for the entire coining system should minimize wedge or total thickness variation to less than 0.12 μm (for products less than 3 mm in diameter).

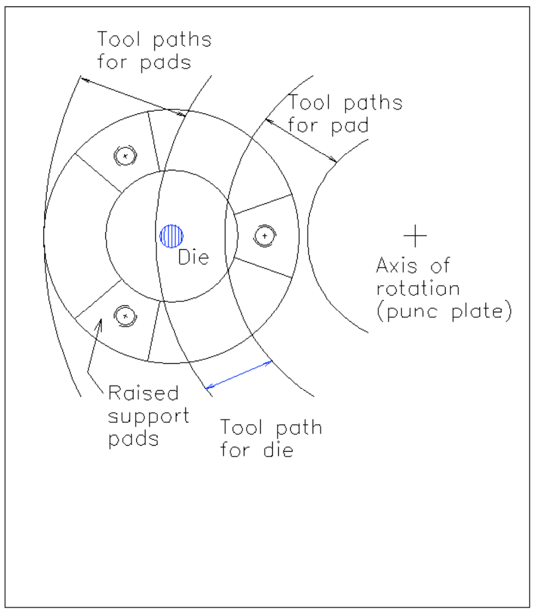

Figure 5. Punch plate, pad, and punch machining schematic.

During the coining operation, load is initiated with a fine-pitch bolt. The bolt presses on a single ball bearing, minimizing the transmission of torque. Load from the bearing is transmitted into a stack of springs. The sensitivity, or gain of the loading system can be tuned with springs arranged in series. Belleville springs are chosen and are preferentially arranged to have the optimum spring rate. The bolt, bearing and springs (Figure 4) push on the end of a rod, which applies force to the bottom of the die plunger. Transferring load to a location near the die surface reduces side-loading and system friction.

Electronic displacement measuring hardware are specified and integrated into the system. In-process measurements capture displacement information during the coining event. The base plate contains a Lion Precision capacitance gage head (Figure 6, see gage head in punch plate) that uses the face of the plunger as reference surface. Sensitivity or gain of the displacement measuring system can be set extremely high (<10 μm full scale) because the distance traveled by the plunger is limited. The electronic amplifier is at null when the plunger/die is gravity fed, and resting on the NNS coin face. As the operation progresses, process feedback can be resolved because of the inherently high system stiffness, low amplitude features and minimal form errors of the blanks (see displacement plot in Figure 7).

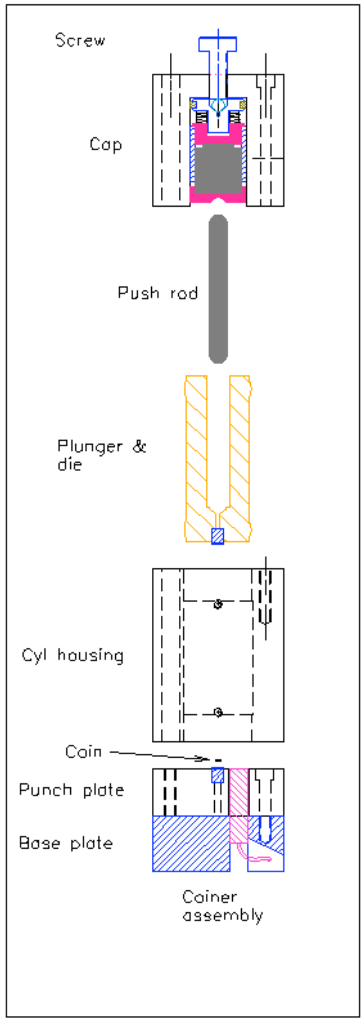

Figure 6. Schematic of the coining system.

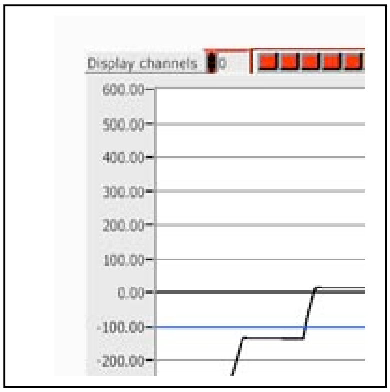

Figure 7. LabView plot of punch and die.

The punch and die elements are installed into the punch plate and plunger using a thermal interference technique. Due to cost and scheduling constraints, the punch and corresponding die were cored and machined from existing nickel-plated aluminum substrates. They are 6.75 mm in diameter x 10 mm long. The 0.75 mm Ni surface is a high phosphorus (approx.13%) chemically plated alloy furnished by Tech Metals Co.

Near-net-shape coin blanks

A series of near-net-shape coin blanks are prefabricated to test the system and process. The near-net-shape blanks are made from aluminum, vanadium, and a low strength, tin-based alloy. The test blanks of moderate precision are processed from commercial sheet stock (Goodfellows Ltd.). The blanks are punched from sheet stock with a cylindrical punch and striker plate. The tin alloy blanks are produced on precision engine lathe by a facing and bonding technique as shown in Figure 8. A single crystal diamond tool is used to produce a low-roughness surface (Al and Pb/tin).

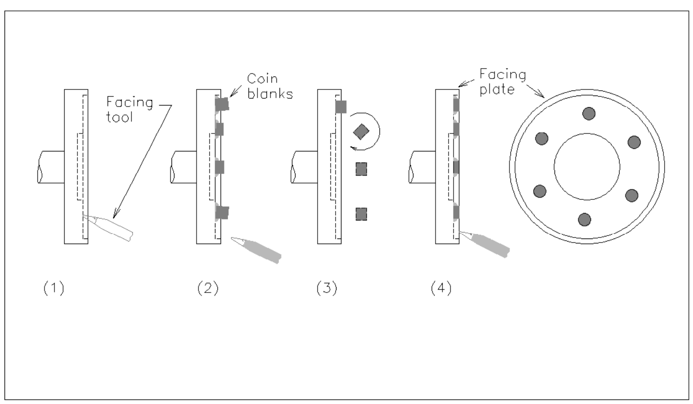

Figure 8. Near-net shape coin blank manufacturing layout.

Finite Element Method Analysis

The process of coining involves a number of key steps in order to produce the desired effects. First, the desired imprint must be defined. Next, a coining press must be designed and fabricated. The press must be rigid and contain a precisely machined die, both flat and contoured. The preparation of the coining blank requires careful handling and close tolerances.

During the coining operation, the coining apparatus will apply a load to the specimen. Initial contact will result in elastic deformation of the specimen as well as some compliance in the apparatus. At some load, the specimen will yield, initiating the process of imprinting the sinusoidal pattern. Continued increase in pressure will increase the level of plastic deformation in the sample. In principle, this process will continue to the point at which the contoured die will fully imprint the desired shape into the sample. Upon unloading, however, elastic deformation of the sample will be released. The amount of springback is likely a function of the elastic modulus of the sample and the compliance of the system. For this reason, finite element simulations were initiated to help guide the design of coining apparatus sinusoidal die.

Model Description

For the analyses presented here, two different models are used. The "Profile Effects" model contains only a small portion of the sample, with the punch profile included. This model is used to calculate the strains and the springback behavior. In addition, a "Total Force" model is also created, which contains the whole sample, but with the punch profile excluded. This model is used to calculate the total force required to perform the coining operation. Both of the models used for this analysis exploit the symmetry of the problem by only modeling one quarter (i.e., 90 degrees) of the cylinder. Hex elements are used for both models, with the models containing the following dimensions:

- Profile Effects model: Circa 7,000 nodes, circa 5,000 elements
- Total Force model: Circa 8,000 nodes, circa 5,400 elements

The models are constrained by having the "bottom" surface totally constrained. In addition, the models are defined with the appropriate boundary conditions for symmetry.

The loading of the sample in this problem is applied to the "top" of the models, and consisted of a specified displacement.

The materials are defined as follows:

- Punch: Nickel, wrought
- Material being coined: Al 1100-o sheet
- Die: Tungsten carbide

The tungsten carbide die is defined as linear elastic (Nike material type 1) and the other two materials are defined as elastic-plastic (Nike material type 3). Both interfaces are defined as sliding with gaps and friction (Nike contact type 3), which means that the surfaces are free to change status (being in contact or not) as necessary. The coefficients of friction are defined as follows (the same for both interfaces):

- Static friction coefficient: 0.6
- Kinetic friction coefficient: 0.4

Figure 9 displays the Profile Effects model geometry.

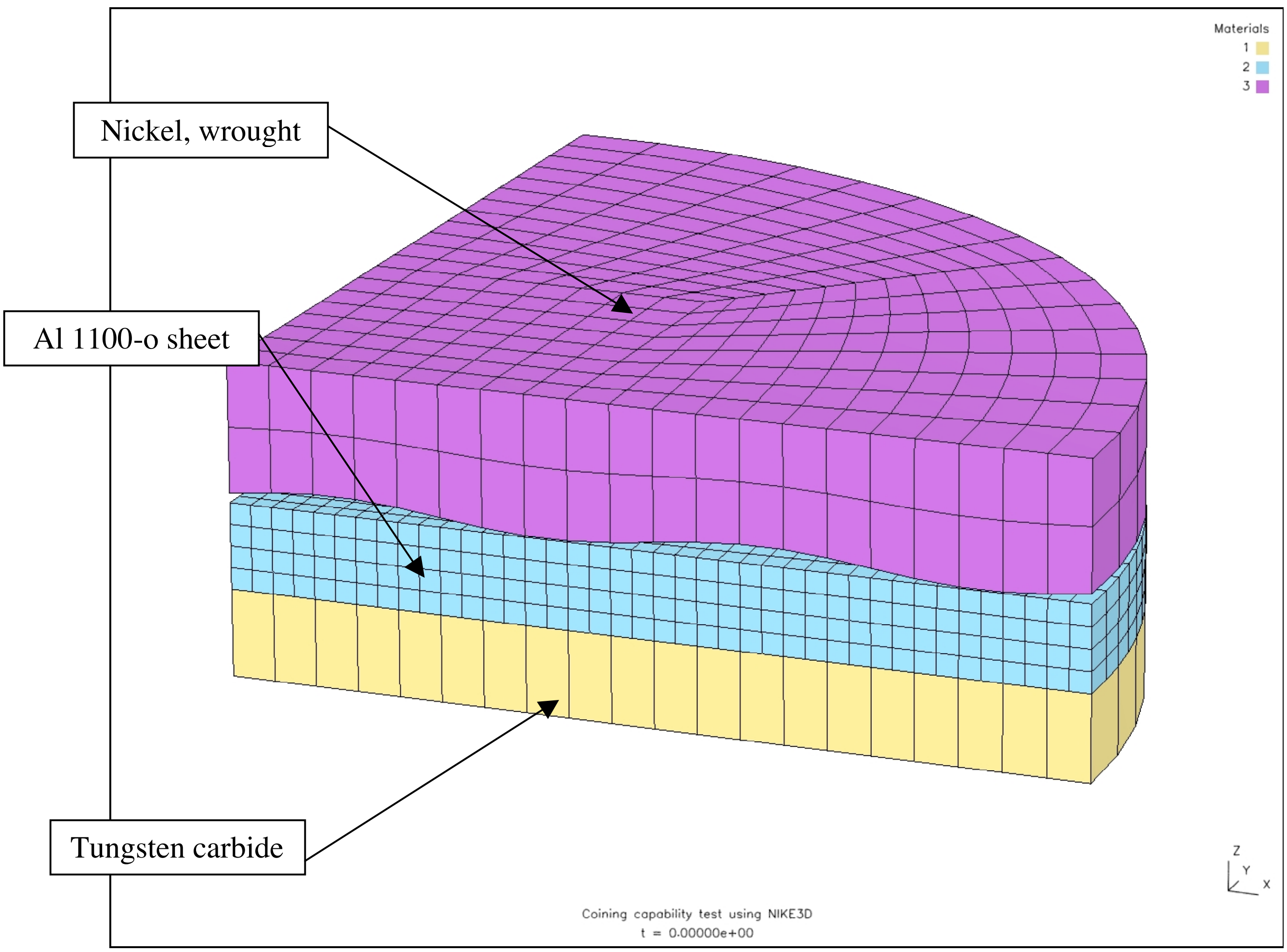

Figure 9: Profile Effects model geometry

Results

The Profile Effects model yields several results. Figure 10 shows the effective plastic strain results.

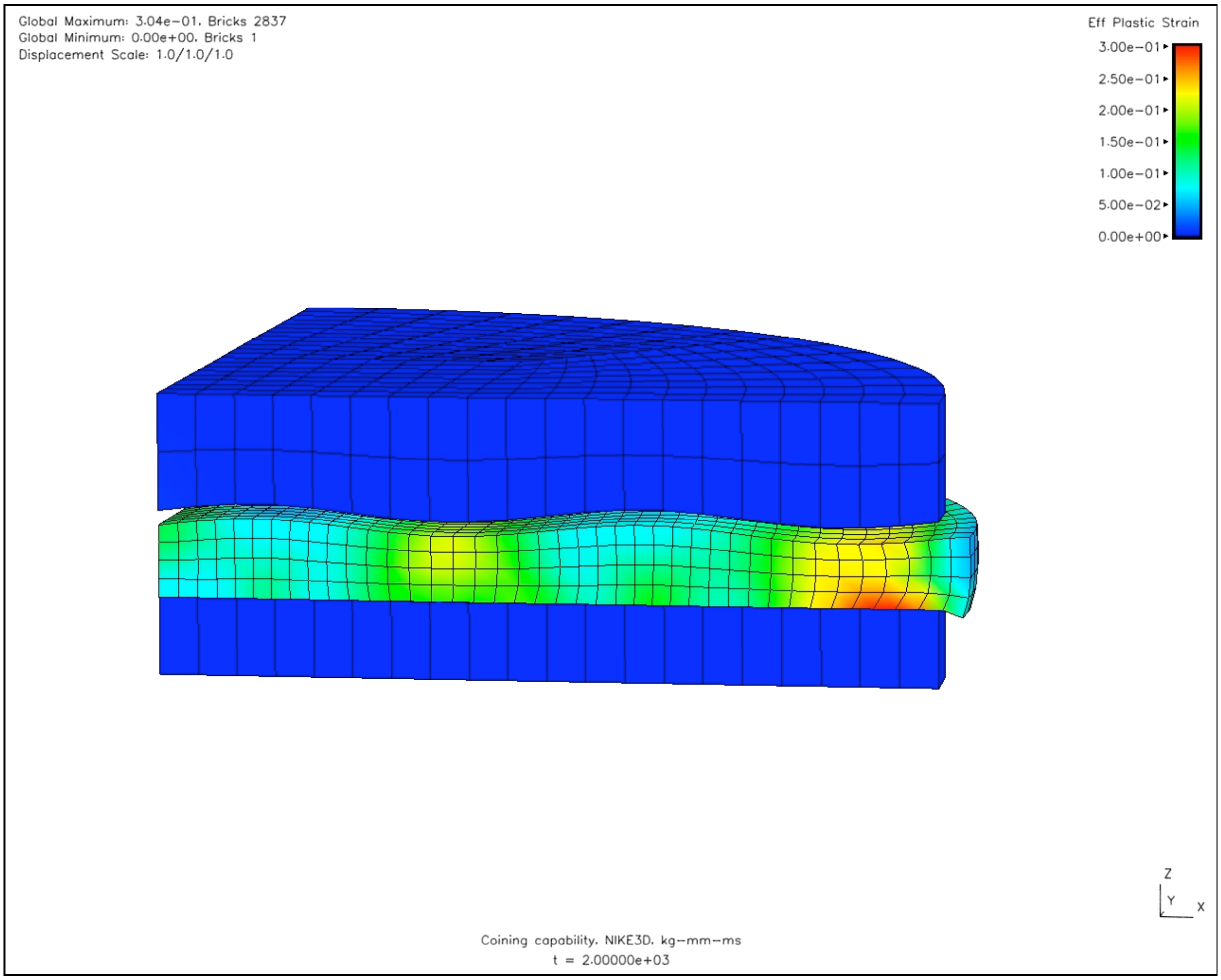

Figure 10: Profile Effects model geometry

Note that this model is generally typical of the results obtained by varying different model parameters. The effective plastic strain is higher under the punch “peaks”, with values between 0.05 and 0.25 across the various runs. Areas of material under the punch “troughs” tend to have lesser values, ranging from 0.05 to 0.15.

Another aspect of investigation is the springback of the pressed surface. Figure 11 displays the springback of the material being pressed.

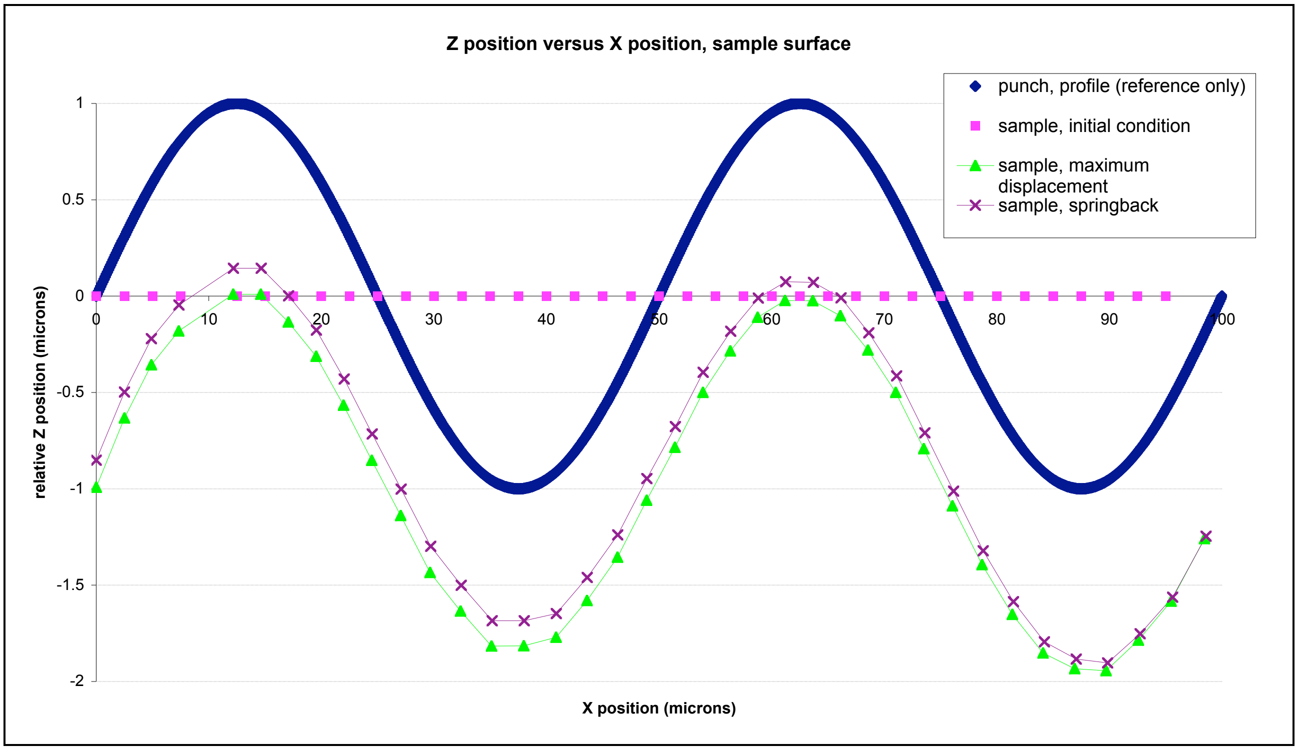

Figure 11. Profile springback

The blue line is the profile of the punch, and is placed in the plot purely for reference. The line comprised of pink squares is the original surface of the Al. The green triangles represent the surface of the Al while still in contact with the punch and at the surface's greatest displacement. Finally, the purple x's show the surface of the Al after the punch has been lifted away. Several observations can be made regarding Figure 11.

- The springback has a magnitude something on the order of 5% of the height of the profile.
- The springback magnitude is not spatially constant. Specifically, the amount of springback decreases as the radius increases. This probably has to do with the fact that the material at the outer edge of the punch and die has somewhere to flow while being compressed; indeed, the material at the center of the sample (X = 0), which has much less opportunity to displace, has a higher amount of springback.

The Total Force model yields only a single result. Figure 12 shows the results from a typical run of the Total Force model. The results from the various Total Force model runs yield a result in the range of 800-1000 lbf.

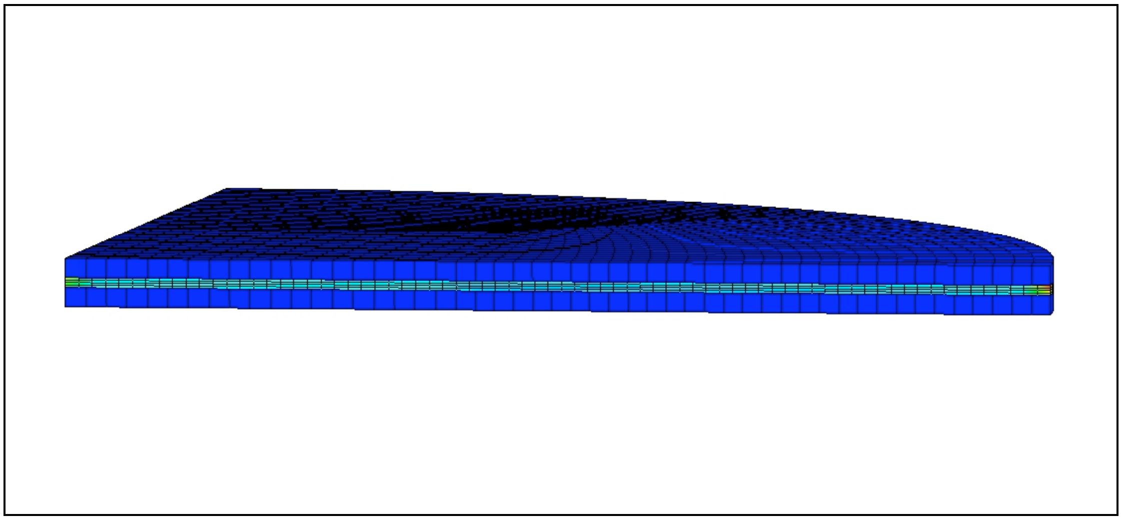

Figure 12: Total Force model results

Coining operation

Figure 6 shows an exploded view of the coining system. The coining process starts with the system disassembled as shown. Disassembly requires three threaded rods (not shown) to be removed by unscrewing nuts at the top, then removing the rods from the punch plate.

The clean, dry near net shape blank is set onto the punch plate die's face. The position of the blank can be centered with the aid by a tool makers microscope.

The housing is set onto the punch plate and rotated to align the three bolt holes. The threads of three studs should be cleaned, greased, and installed through the holes in the housing into the punch plate. The housing is assembled onto the studs and vertically slid onto the punch plate. The die plunger is inserted into the housing bore and lowered carefully downward until it rests on the coin blank. The push rod is installed into the center of the plunger. The screw in the cap can be loosened prior to assembling the assembly onto the studs. The three stud nuts are installed and a torque applied to 35 ft.lb. The screw is hand tightened, then advanced with a wrench until the desired force is displayed by the load cell amplifier read-out. The unit is carefully disassembled with care taken to not rotate or re-contact the finished coined product. The finished products have not adhered to the punch or die surface, but "floating" the coin on a film of alcohol can help the process and provide a liquid hydrodynamic barrier for protection.

Testing and Results

A series of tests have been preformed to evaluate coining hardware and process. Three materials were considered: aluminum, a tin-lead alloy, and vanadium. Aluminum is selected because of its well-known properties and characteristics. The tin/lead alloy and vanadium are chosen because of programmatic applications. Three series of samples have been prepared for testing;

1) Tin/lead solder- 3 mm diameter, 24 um thick
2) 1100 series aluminum – 2 mm diameter, 20 um thick
3) Vanadium – 1 mm diameter, 20 um thick

Conservative coining pressures were used to avoid damaging (yielding) the punch and die surfaces. We also started with the softer materials, postponing the harder vanadium for last. A several "coins" were produced under identical conditions. This proved that the mechanical, metrology, and force measuring systems provided sufficient repeatability, resolution, and minimal hysterisis (data not shown).

A typical displacement measurement plot taken during a coining event (Figure 7) shows the effect of load. The capacitance gage head is anchored into the punch plate and "reads" the position of the die. The system was loaded in increments of 100 lbs., then un-loaded to evaluate the effect of displaced of material.

Measuring the thin, freestanding products for total thickness variation is challenging and no measurements were attempted on the test coins. A WYKO surface profilometer and optical microscopes were used to inspect overall appearance and profile. The 1-micrometer (Peak to Valley) sine wave profile on the die surface is pressed into the test blank surface**.** Figure 13 shows profile traces for the punch and resulting coined surface (note difference the plots in vertical scale). For the earlier aluminum and tin/lead tests, the trend showed about 94% conformance over the entire coin surface. The outer one-third of the part showed defects caused by inclusions in the parent material. The micrograph (Figure 14) shows residual surface roughness in the central area. This effect is due to scratches, and profile defects in the pre-coined blank. The vanadium test proved weakness in the structural integrity of the composite punch and die design. The pressure required to produce full definition yielded the punch surface. The outer area of the coined blank measured the same as the other materials, however the central area exhibited excessive residual roughness (0.15 μm Ra) and only partial imprinting (0.6 micrometers P-V min.). Learned information (data offered by the U.S. Denver Mint) supported the results from the abbreviated tests. Friction is known to increase the pressures required to produce fully formed products[1]. The plot (Figure 15) shows the importance of managing friction for high-aspect ratio coined products (note that the vertical line (disk)).

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[1] Rebecca Weiss US Denver mint

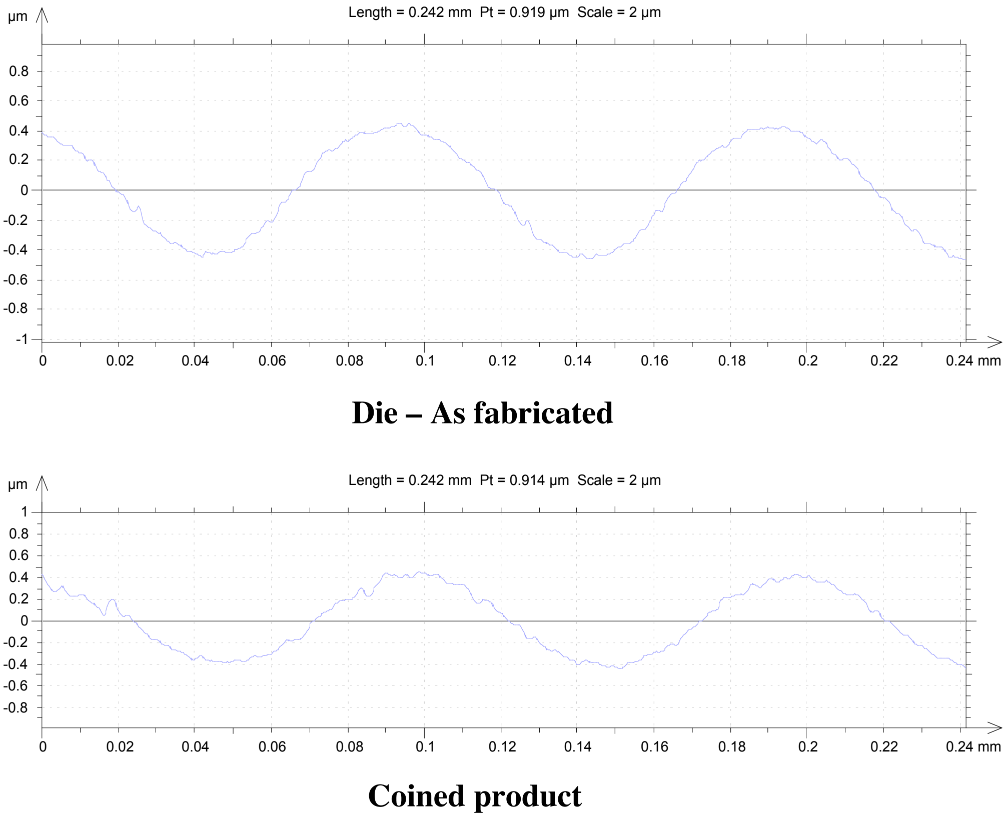

Figure 13. WYKO micro-PMI line traces of punch and coined product (note scale)

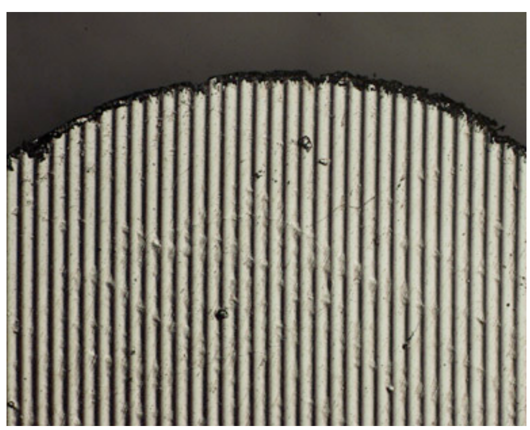

Figure 14. Micrograph of coined surface (2mmdia)

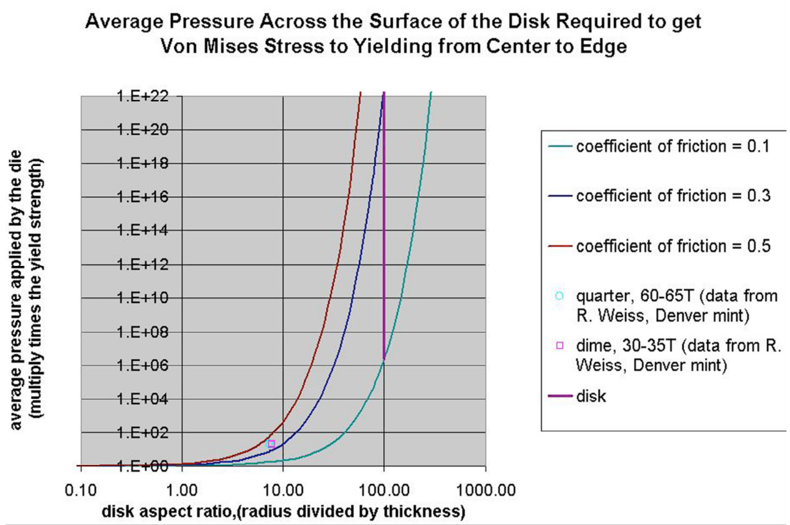

Figure 15. Plot showing coining pressures for currency and LLNL product[2]

The first disc-shaped parts to be coined were punched from precision rolled foil of commercially available 1100 series aluminum. Pressing a 3 mm diameter by ≈100-µm thick disc to 500 lbs. of pressure produced a flat part with a 1-µm deep by 50-µm period sine wave pattern covering all of the surface. Figure 16 is a low magnification optical micrograph quarter section of the 3 mm disc showing the sine wave pattern on the surface.

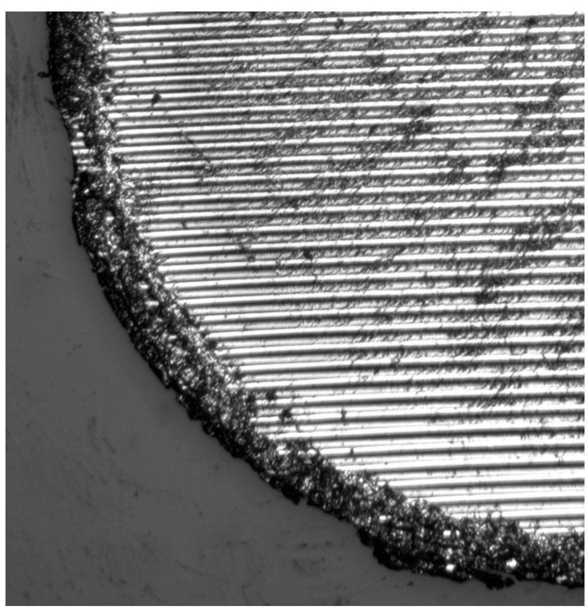

Figure 16. Optical micrograph of the coined surface of the 1100 series aluminum.

[2] Plot from Jim Hamilton

Throughout the sine wave pattern is a considerable amount of roughness. The various surface features that contribute to this roughness can be more clearly seen in Figure 17.

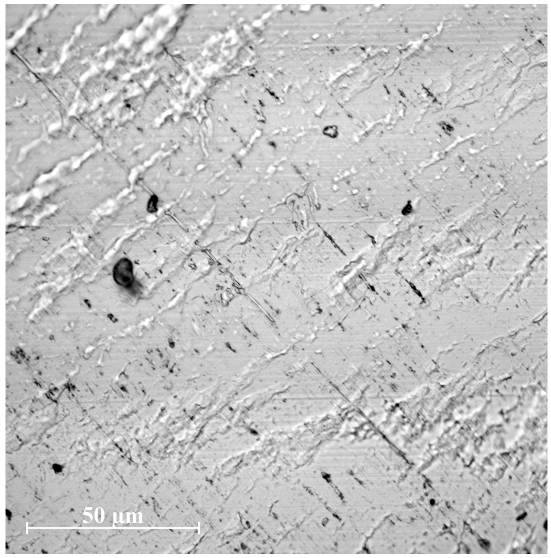

Figure 17. Surface roughness is visible on the starting target blank.

There are basically four sources of roughness that can be identified in Figure 17. The rolling marks from the foil production can be seen as dark broken up lines running from the upper left to the lower right. The wrinkles and micro-cracking in the surface can been seen normal to the rolling direction. Again, this is a product of the production of the foil. Most of the black spots are precipitates that reside in the material. Some of the black spots are surface contamination or debris from poor housekeeping.

Realizing that the staring surface quality greatly affects that quality of the surface contour, we polished several discs of aluminum 1100 series material prior to coining. The polishing procedure is as follows. Discs were mounted to a lapping fixture using a low temperature melting wax. The samples were flattened by course grinding with 600 grit SiC paper followed by lapping with 800 grit SiC paper. The mounted samples were then put on an automated polishing system and polished with 1-µm diamond paste on a nylon cloth until all of the 800 grit scratches were gone. A final polish was performed using 0.05-µm Al_2O_3 abrasive on a felt cloth until all of the 1-µm scratches were gone. A disc specimen was then pressed to 400 lbs. A full sine wave was pressed with the overall surface quality being much better than the previous rolled foil. Figure 18 is an example of a fully pressed sine wave on this specimen.

Figure 18. Sinusoidal pattern imprinted on a well-polished specimen of 1100 aluminum.

It can now be seen that the surface roughness is now only limited to the precipitates and surface debris. Where the precipitates lie on the surface it can be seen that there is irregular deformation thus distorting the sine wave profile. In Figure 19, the surface debris can be more easily seen as well as the fine-scale machining marks from the production of the sine wave die.

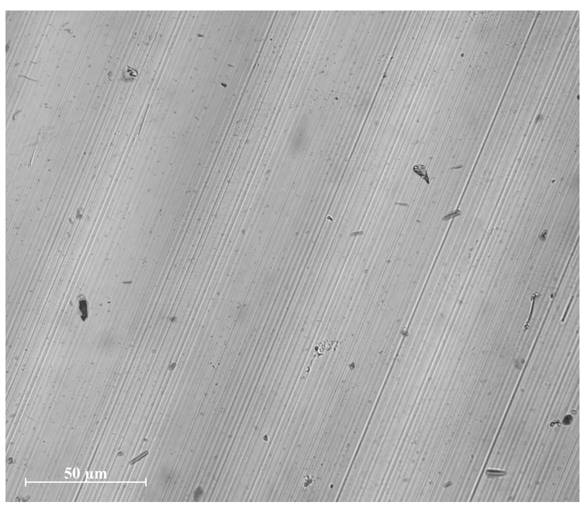

Figure 19. Surface debris is visible on the surface of an imprinted sample of 1100 aluminum.

SNM coining

Metallographic polishing was performed on a 3-mm diameter piece of SNM in order to get a similar surface finish as on the aluminum prior to coining. Difficulties arose during polishing because of the formation of a hydride layer on the surface of the

SNM. Ion etching was used to remove the hydride layer, estimated to have been 1-2 μm thick. After ion etching, a surface topography developed as seen in Figure 20.

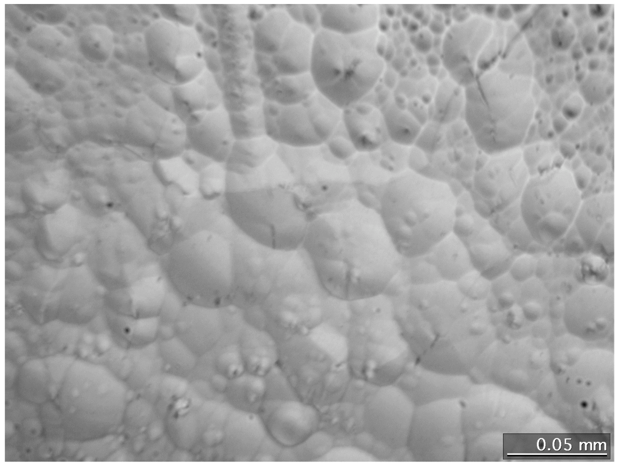

Figure 20. Surface roughness is visible as a result of ion etching.

The SNM disc was then pressed to 500lbs. In Figure 21, a fairly rough sine wave has been pressed into the surface of the SNM sample. The roughness in these images appears to be from another source though. The wrinkles we believe are from the hydride precipitates that formed during preparation that grew down into the grain boundaries of the material, thus not being removed by the ion etching. Additionally, that starting dimpled surface may have contributed to the wrinkles. Secondly, there are groupings of fine scale line features in random directions in the sample. These can be more easily seen in Figure 22. We believe that these may be from a solid-state transformation of the SNM to a different crystal structure. Finally, there are some precipitates in the material and surface debris that appear as black spots in the image.

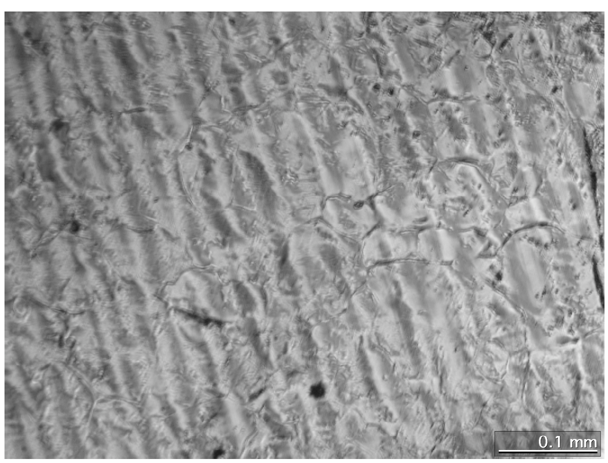

Figure 21. Surface roughness remains visible after coining.

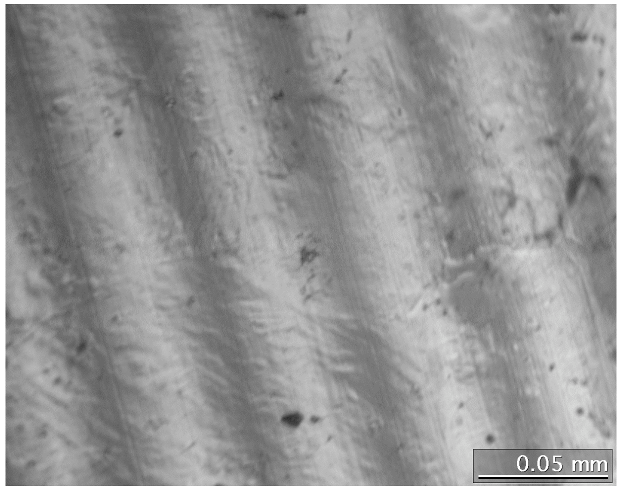

Figure 22. Fine-scale surface roughness likely due to a partial solid state phase transformation.

Recommendations for Future Study

1) The rear surface of the embossed coin exhibits waviness. This may be an effect of localized deformation of the planar die surface. The die may be yielding along the lines of peak pressure. Modeling and substitution of a harder lower die surface is recommended.

2) Full amplitude features were not present in the coined products. This may also be an effect of deformation. Again, the lines of peak pressure may be compressing during the process. Additional finite element modeling should guide the upper die design.

3) The composite punch and dies used in this investigation are too malleable for use on materials with moderate yield strength. Silicon should be considered because of stiffness, young's modulus (1000Knoop, 19.6Msi). The material has good diamond turning/machining characteristics and can also be ultra-precision formed with many other lithographic etching and sputtering techniques.

4) Metrology is critical to understanding the coining process. Form measurements for both sides of the product should be related numerically. Dual surface interferometer is being developed under a ROI.

5) The actual "fill point" where the contours of the punch are totally filled may not be measured with the current "high gain" displacement measuring system. This event may not be resolvable.

6) The tests were conducted to successfully prove the principle of this process. Better near-net-shape blanks, more experiments, and comprehensive documentation is needed.

7) Several references on metal forming indicate that it should not even be possible to coin a sample with the aspect ratio as is being used here. The analysis and several actual coining tests seem to indicate otherwise. A deeper understanding of the coining process requires a reconciliation of these conflicting pieces of information.

8) The results of the Total Force model are highly dependent on the values of the coefficients of friction used. The values used in this study are general metal-on-metal values, and should be checked against values specific to the materials and conditions being used here.

9) Both models, but especially the Total Force model, seem to be somewhat unstable (i.e., small changes in parameter values seem to cause very large changes in the results). This is typically a sign that a model has issues that need to be corrected. These issues could be any one or more of a number of things, including computational issues (solver parameters, convergence tolerances, mesh issues, etc.) or problem parameters (incorrect values of physical quantities, incorrect assumptions regarding the physics of the system being modeled, or trying to model a system which is actually unstable).

10) Due to time constraints, the mesh density of the Profile Effects model was kept rather small. Increasing the mesh density of the material of interest may yield more insight into its behavior.

11) Finally, there are some additional system characterization questions that can be investigated using these models:

- How does the behavior of the system change if different materials are used?
- What happens to the material of interest if the shape of the punch profile changes?
- What happens to the material of interest if the operation takes place at different temperatures?
- How does the response of the material of interest change with loading rate?